

Application of polarization to the MODIS aerosol retrieval over land

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Summary

Atmospheric aerosols are intimately linked to Earth's climate system, hydrological cycle, and to the well being of Earth's inhabitants. However, aerosols are difficult to study on a global scale because they are inhomogeneous on all temporal, horizontal and vertical scales. Satellite measurements are increasingly important to the study of aerosols in Earth's system, because they can view large parts of the globe within a short time span. Passive sensors, such as the Moderate Imaging Spectroradiometer (MODIS), measure reflection of radiation from the top of the atmosphere (TOA), and do not disturb the ambient aerosol composition. Over land surfaces, MODIS observed reflectance in two visible channels (blue and red), and one mid-IR channel, are used to derive aerosol optical thicknesses (AOT) and other aerosol properties. The measured spectral reflectance is compared with theoretical TOA reflectance, calculated assuming non-polarized (scalar) radiative transfer (RT) through the atmosphere. In the red and IR wavelengths, the neglect of polarization introduces only minor errors to the simulated reflectance. However, in the blue, molecular and aerosol multiple scattering dominate the TOA signal, leading to potentially large polarization effects. Using a RT code that allows for both vector and scalar calculations, we examined the reflectance differences at the TOA, with and without polarization. We found that the differences in blue channel TOA reflectance (vector – scalar) may reach values of 0.01 or greater, depending on the sun/surface/sensor scattering geometry. Reflectance errors of this magnitude translate to AOT differences of 0.1, which is a very large error, especially when the actual AOT is low. As a result of this study, the next version of aerosol retrieval from MODIS over land will include polarization.

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Abstract

Reflectance measurements in the visible and infrared wavelengths, from the Moderate Resolution Imaging Spectroradiometer (MODIS), are used to derive aerosol optical thicknesses (AOT) and aerosol properties over land surfaces. The measured spectral reflectance is compared with lookup tables, containing theoretical reflectance calculated by radiative transfer (RT) code. Specifically, this RT code calculates top of the atmosphere (TOA) intensities based on a scalar treatment of radiation, neglecting the effects of polarization. In the red and near infrared (NIR) wavelengths the use of the scalar RT code is of sufficient accuracy to model TOA reflectance. However, in the blue, molecular and aerosol scattering dominate the TOA signal. Here, polarization effects can be large, and should be included in the lookup table derivation. Using a RT code that allows for both vector and scalar calculations, we examine the reflectance differences at the TOA, with and without polarization. We find that the differences in blue channel TOA reflectance (vector – scalar) may reach values of 0.01 or greater, depending on the sun/surface/sensor scattering geometry. Reflectance errors of this magnitude translate to AOT differences of 0.1, which is a very large error, especially when the actual AOT is low. As a result of this study, the next version of aerosol retrieval from MODIS over land will include polarization.

1. Introduction

Atmospheric aerosols are intimately linked to Earth's climate system, hydrological cycle, and to the well being of Earth's inhabitants (e.g. IPCC, 2001; Ramanathan et al., 2001; Samet al., 2000). However, aerosols are difficult to study on a global scale because they are inhomogeneous on all temporal, horizontal and vertical scales. Satellite measurements are increasingly important to the study of aerosols in Earth's system (Kaufman et al., 2002; King et al., 1999), because they can view large parts of the globe within a short time span. Passive sensors, such as the Moderate Imaging Spectroradiometer (MODIS) (Salamonson et al., 1989), measure reflection of radiation from the top of the atmosphere (TOA), and do not disturb the ambient aerosol composition. As compared to previous satellite sensors used for aerosol retrieval, (such as the Advanced Very High Resolution Radiometer (AVHRR; e.g. Stowe et al., 1997), MODIS has a much wider spectral range (0.412 to 15 μm), finer spatial resolution (up to 250 meters) and is calibrated to a much higher accuracy. Thus MODIS is a premier instrument for estimating the spectral aerosol optical thickness (AOT), leading to estimates of aerosol size parameters.

MODIS retrieves clear sky (non-cloudy) aerosol optical thickness (AOT) over ocean and land, using two separate algorithms (Kaufman et al., 1997; Tanre et al., 1997; Levy et al., 2003; Remer et al., submitted 2003). Nominal products include the AOT at 0.55 μm , and the aerosols' fine mode contribution to the total AOT, or fine mode weighting (FMW). AOTs, calculated by each of these algorithms, have expected error bars (Kaufman et al., 1997, Tanre et al., 1997) which have been "validated" (Ichoku et al., 2002; Chu et al., 2002; Remer et al., 2002; Remer et al., submitted 2003) when compared to ground based sunphotometers, such as those of the AERosol Robotic NETwork (AERONET: Holben et al., 1998). Over non-dusty ocean sites, global MODIS/AERONET AOT regression lines have slopes near one, offsets near zero, and correlation coefficients of 0.9 and above. Over land sites, the global MODIS/AERONET regression has an offset about 0.1, slope about 0.8, and correlation coefficients of about 0.6.

Why is the MODIS/AERONET comparison so much poorer over land surfaces? A large portion of the y-offset error is due to poor assumptions about the land surface reflectance properties, and will be addressed in a future study. The less than one slope may be partially repaired by introducing updated aerosol optical models (Levy et al., submitted 2003; Ichoku et al., 2003).

Here, we address the errors introduced by simulating MODIS over-land observations by a radiative transfer (RT) code that neglects polarization. For atmospheric correction of satellite imagery, Fraser et al., (1989) suggested errors up to 10% in blue wavelengths. Lacis et al., (1998) claimed that in a pure Rayleigh atmosphere, clear sky radiance errors would also be as much as 10%, dependent on scattering geometry. Yet, for computation of radiative fluxes (integration of all scattering angles), the errors would be cancelled out. Our study analyzes vector – scalar differences, using appropriate scattering geometry for MODIS. Errors introduced by scalar RT are calculated for both blue and red channels, under a variety of AOTs. Also, we examine whether scalar RT errors could be responsible for the poor validation results.

2. The MODIS aerosol lookup tables

The MODIS aerosol retrieval algorithm combines two separate algorithms, one each for over ocean and over land. The basic strategy for both algorithms is the lookup table (LUT), wherein TOA spectral reflectance is simulated by radiative transfer (RT) code. Included in the RT calculations are assumptions about the surface reflectance, molecular scattering and aerosol scattering/absorption (functions of assumed aerosol chemical and size parameters). For each MODIS pixel of suitable quality (Remer et al., submitted 2003), the retrieval algorithm attempts to mimic the observed spectral reflectance with values from the LUT. Minimum total differences between the two spectral quantities lead to solutions of spectral AOT and FMW.

The current LUT tables for ocean and land were computed using separate RT codes. Over land, the lookup tables were calculated using the scalar version of the RT code formulated by Dave (1970). Its use has long been a standard in the remote sensing community, desirable because it was well understood. It was also easily updated for creating the MODIS lookup tables. Polarization was not seen to be a major issue, because

previous aerosol instruments operated in the red and IR wavelengths (e.g. 0.64 and 0.84 μm for AVHRR). Under single scattering assumptions (low AOT), the inclusion of polarization would make little difference to the simulated TOA reflectance. Indeed, differences between Dave's vector (1970) and scalar codes were less than 3% for wavelengths $\lambda \geq 0.64 \mu\text{m}$ (Fraser et al., 1989).

3. Atmospheric Polarization applied to MODIS over land

Fraser et al., (1989) pointed out, however, that under conditions of large optical depths, the increasing dominance of multiple scattering leads to larger errors in scalar assumed radiances. Due to a large Rayleigh optical depth (about 0.2), multiple scattering is always present in the blue, leading to a 10% error at 0.486 μm . Lacis et al., (1998) suggested a maximum error when the total atmospheric optical thickness is near unity, with lesser errors under even higher optical thickness. These effects were accounted for when creating the MODIS LUTs over ocean, but not over land. Here, we attempt to quantify the effects of neglecting polarization within the atmosphere, as applied to the over-land LUT. Note that polarization arising from the land surface is not examined here.

The vector version of the Dave code has not been appropriately maintained, so it is not a suitable code for this study. Instead, we use the polarized atmospheric radiative transfer model (RT3) of Evans and Stephens (1991). This plane-parallel, adding/doubling code is desirable for this study, because polarization can be turned on or off by changing only one line within an input file. The other inputs, including the wavelength, aerosol parameters, surface reflectance and atmospheric profiles, are either included within the input file, or computed offline.

Aerosol optical properties were computed offline by the Mie vector (MIEV) code described by Wiscombe (1980). We used 3000 size bins, logarithmically spaced from $r_{\min} = 0.0084 \mu\text{m}$ to $r_{\max} = 56.042 \mu\text{m}$, having intervals of $d_{\ln r} = .002937$. The complex refractive index was set at $1.45 - 0.0035i$. The aerosol size distribution was modeled as the "water soluble mode of the continental model", where $r_g = 0.005$, $r_v = 0.176$, and $\sigma = 1.09$ (Kaufman et al., 1997; Lenoble and Brogniez, 1984). Colarco et al., (2002), used the same combination of RT3 and MIEV codes for modeling Saharan dust.

For the atmospheric profile (temperature, pressure, humidity), we assume the U.S. Mid-latitude summer profile. Aerosols were placed within this model atmosphere, with a maximum concentration at 2 km. The land surface was assumed Lambertian, having spectral reflectance of 0.04 and 0.07, for blue and red, respectively (e.g. Levy et al., submitted 2003). The Rayleigh optical thickness was calculated offline and set at 0.194 and 0.047 for the two wavelengths, respectively. Together, Mie and Rayleigh theory yielded optical thicknesses and phase matrices representing each level of the model atmosphere. This exercise was repeated for multiple values of AOT.

The TOA spectral reflectance was calculated by both the scalar and the vector versions of the RT3 code. Plotted in Figures 1a and 1b are the TOA blue and red

reflectance as a function of the view zenith angle, for both vector (solid lines) and scalar (dashed lines) implementations of RT3. In both plots, $\theta_0 = 30^\circ$ and $\tau = 0.2$. For Figure 1a, the satellite and sun are located in opposite parts of the sky, so that in regard to the direct radiative path, the relative azimuth angle $\phi = 25.7^\circ$. For Figure 1b, the satellite and sun are near each other ($\phi = 154.3^\circ$), producing a sharper scattering angle. Reflectance differences between vector and scalar cases run as high as 0.006 in the blue, with reversed signs depending on the scattering geometry. Polarized reflectance increases relative to nonpolarized reflectance when the sun and satellite are on the same side of the sky (and scattering angles are larger). Note that the magnitudes of the vector – scalar differences are much smaller for the red as compared to the blue. Figures 2 and 3 draw contours of vector – scalar reflectance differences, as functions of both solar and satellite view angles. Figures 3a and 3b show differences in the blue, for $\phi = 25.7^\circ$ and $\phi = 154.3^\circ$, respectively. Figures 4a and 4b plot differences in the red. Contour magnitudes in the blue are ten times those in the red. And like the single solar zenith plots, the signs of the contours are reversed whether the satellite and sun are near each other in the sky. Maximum absolute values of the contours are over 0.01 in the blue, which correspond to a potential 0.1 error in retrieved AOTs (e.g. Kaufman et al., 1997b).

Indeed, for the continental aerosol case used in this simulation, vector-scalar differences can reach 0.03 in magnitude, and be either positive or negative. Yet, for all the angles we calculated, the average vector-scalar differences are close to zero! Figure 4 displays the extreme and average values of vector-scalar differences for a given AOT within the angles we calculated, as a function of AOT. Also plotted are the maximum (magnitude) differences that would yield a retrieval of AOT within expected errors, defined here as $0.05 + 0.2\tau$ (Chu et al., 2002). The 0.03 magnitude vector-scalar difference suggests that by neglecting polarization in the blue, retrievals of AOT would have inappropriately large errors for AOT less than unity

However, MODIS should observe all possible solar/surface/satellite scattering geometries during its yearly orbit. Figure 4 demonstrates that the average difference in TOA reflectance, due to the neglect of polarization, is close to zero. In a global sense, then, we would not expect retrieval bias due to the neglect of polarization. Computation of radiative fluxes should also display no bias (Lacis et al., 1998).

4. Discussion and Conclusion

We have applied a well known radiative transfer code to study errors of MODIS aerosol retrievals over land. Specifically, we have examined the errors produced by neglecting atmospheric polarization during creation of the MODIS lookup tables. As noted before by Fraser et al., (1989), the neglect of polarization in the red channel does not cause large errors in TOA reflectance. In the red, the Rayleigh optical thickness is small, resulting in little polarization of the signal. Yet in the blue, where Rayleigh optical thickness is much larger, the neglect of polarization does produce large errors for the TOA reflectance. These errors can be as large as 0.03 for large solar zenith and view zenith angles, which is equivalent to a very large AOD retrieval error of 0.3. In addition, these errors may be positive or negative depending on the specific scattering geometry. Fortunately, errors for near-nadir solar and satellite zenith angles are much smaller,

nearly negligible. This means that we can expect errors as high as ± 0.3 in extreme cases in the MODIS derived aerosol optical thickness over the land.

For long term and global measurements, however, the positive and negative errors will cancel out. Thus, calculation of aerosol statistics on large spatial and long temporal scales should be possible, with little bias. Also, this means that calculating the large scale aerosol radiative forcing calculations from satellite measurements is an appropriate endeavor.

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Polarization Figures

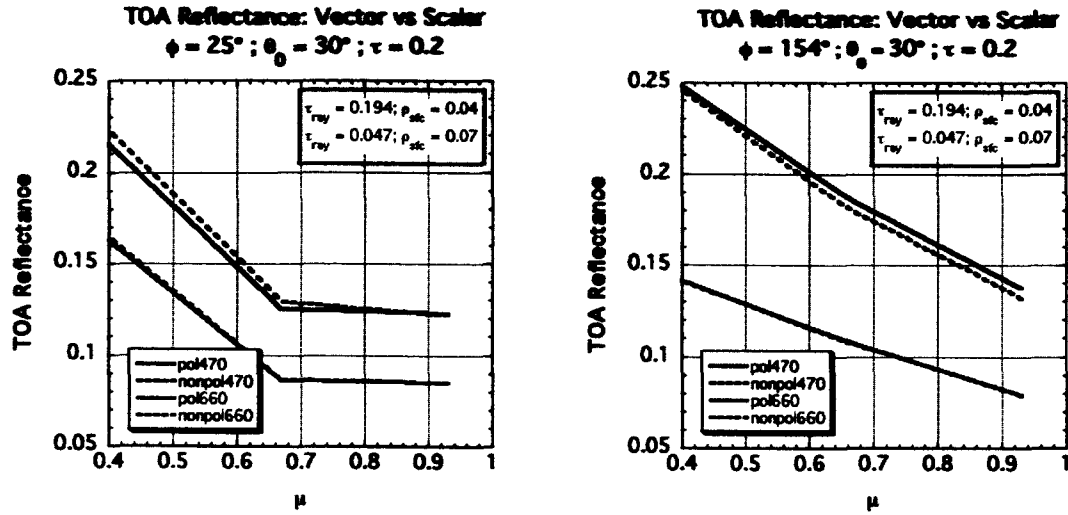


Figure 1: Top of the atmosphere blue and red reflectance, as a function of the view angle, for two different relative sun/satellite relative azimuth angles; a) $\phi = 25.7^\circ$ and b) $\phi = 154.3^\circ$. In both cases the solar zenith angle, $\theta_0 = 30^\circ$, and the AOT, $\tau = 0.2$. The Rayleigh optical thicknesses are 0.194 and 0.047, respectively, and the surface reflectance values are 0.04 and 0.07. The solid line represents the vector case, while the dashed line is the scalar case.

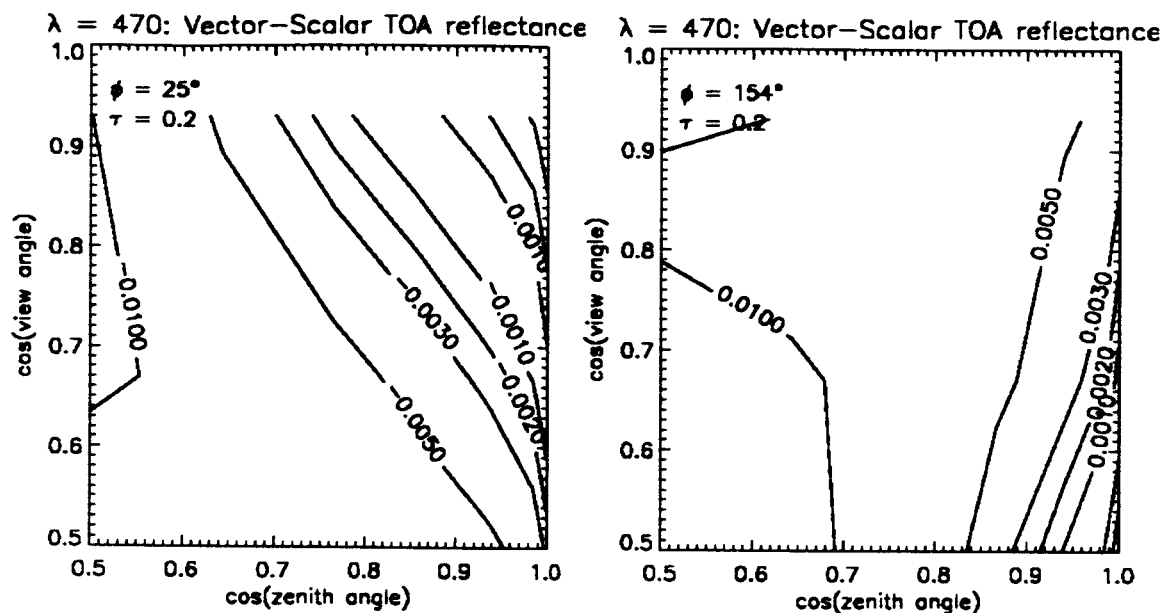


Figure 2: Contour plots of the differences (vector – scalar) between RT3 calculations of TOA blue reflectance, as a function of both the view and solar zenith angles a) $\phi = 25.7^\circ$ and b) $\phi = 154.3^\circ$. In both cases the solar zenith angle, $\theta_s = 30^\circ$, the AOT, $\tau = 0.2$, the Rayleigh optical thickness is 0.194, and the surface reflectance is 0.04. Note the signs of the contours.

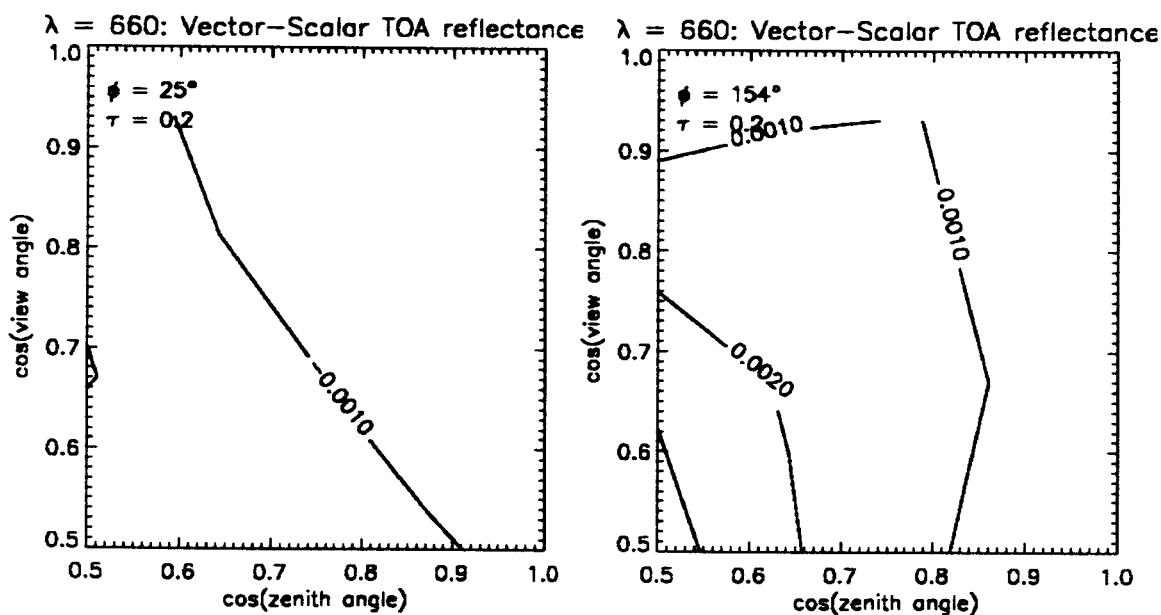


Figure 3: Similar to Figures 3a and 3b, but for red reflectance. The Rayleigh optical thickness is 0.047, and the surface reflectance is 0.07.

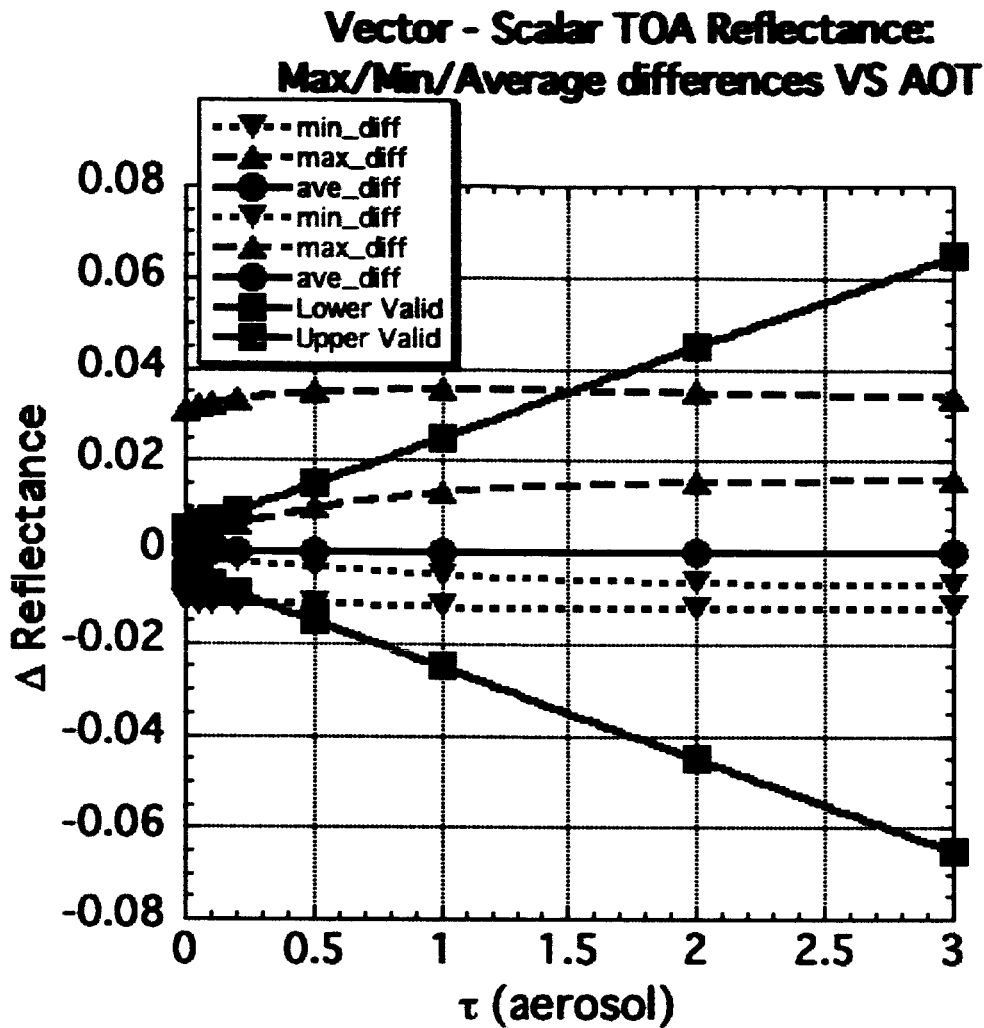


Figure 4: Maximum, Minimum and Average differences for vector-scalar calculated TOA reflectance, as a function of AOT. Blue and red represent blue and red wavelengths. The green lines represent the maximum Δ Reflectance that would lead to AOT retrieval errors within the expected AOT error. $\Delta\rho \approx ((0.05 + 0.2\tau) / 10)$